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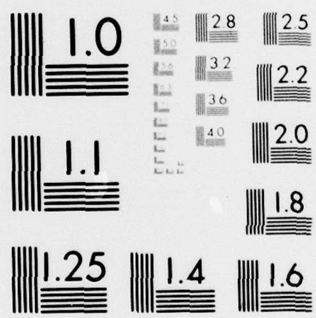

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FATIGUE STRENGTH OF TRIP STEELS

GREGORY B. OLSON, RICHARD CHAIT, MORRIS AZRIN, and
ROGER A. GAGNE

June 1979

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ABSTRACT

Comparison of the S-N curves of warm-extruded TRIP steels, heat treated to give two stabilities with respect to deformation-induced martensitic transformation during testing, reveals a beneficial effect of the transformation on fatigue behavior under stress control conditions. The proportionality of fatigue strength to ultimate tensile strength is maintained to higher strength levels relative to other steels. For a stress ratio of R = 0.1, a fatigue strength at 10^7 cycles of 180 ksi (1,240 MPa) is obtained.

to the seventh power

INTRODUCTION

Studies[1-6] of the fatigue behavior of metastable austenitic steels have shown interesting differences between the behavior of high-strength TRIP steels[7] and that of lower strength metastable austenites, while identifying a marked contrast between the influence of the deformation-induced martensitic transformation under strain-control versus stress-control conditions. Fatigue crack propagation (FCP) studies (controlled ΔK) have indicated that the deformation-induced transformation retards crack propagation in the lower strength austenites, particularly at low ΔK,[1] and also exerts a beneficial influence in high-strength TRIP steels, though to a much lesser extent.[2] In smooth bar fatigue tests on lower strength austenites, the transformation was found to reduce fatigue life under conditions of controlled plastic strain amplitude.[3] Under controlled *total* strain amplitude, the transformation was found to be detrimental to low cycle fatigue life, but it was indicated that a small amount of transformation may be beneficial at high cycles.[4] Similarly, the low cycle fatigue properties of high-strength TRIP steels were found to be degraded by the deformation-induced transformation under controlled total strain amplitude conditions.[5] Under *stress* control, however, the fatigue life of the lower strength metastable austenites is found to be greatly enhanced by the transformation; for smooth bar tests with a stress ratio of $R = 0$, fatigue limits in excess of the yield strength have been reported.[6] This study was undertaken to extend the stress-control fatigue tests to the high-strength TRIP steels and determine whether the beneficial effect of the deformation-induced transformation persists to the high strength levels. In addition, fatigue data generated under stress-control conditions may provide a more useful design criterion for many applications.

MATERIALS AND PROCEDURE

Both air and vacuum melts were prepared of a TRIP steel of nominal composition: Fe-9Cr-8Ni-4Mo-2Mn-2Si-0.3C. Ingots were homogenized at 2300 F (1530 K) for 6 hours, press forged to 3-3/8 in. (8.58 cm) diameter at 2100 F (1420 K), and machined to 3-1/8 in. (7.93 cm) diameter billets. The billets were extruded to 1-1/4 in. (3.18 cm) diameter at 2100 F (1420 K), solution treated at 2250 F (1510 K) for 1 hour and water quenched. The solution-treated austenitic billets were then strengthened by warm extrusion to reductions of area of 40%, 60%, or

1. PINEAU, A. G., and PELLOUX, R. M. *Influence of Strain-Induced Martensitic Transformations on Fatigue Crack Growth Rates in Stainless Steels.* Met. Trans., v. 5, no. 5, 1974, p. 1103-1112.
2. CHANANI, G. R., ANTOLOVICH, S. D., and GERBERICH, W. W. *Fatigue Crack Propagation in TRIP Steels.* Met. Trans., v. 3, no. 9, 1972, p. 2661-2672.
3. BAUDRY, G., and PINEAU, A. G. *Influence of Strain-Induced Martensitic Transformation on the Low-Cycle Fatigue Behavior of a Stainless Steel.* Materials Science and Engineering, v. 28, no. 2, 1977, p. 229-242.
4. HENNESSY, D., STECKEL, G., and ALTSTETTER, C. *Phase Transformation of Stainless Steel During Fatigue.* Met. Trans. A., v. 7A, no. 3, 1976, p. 415-424.
5. CHANANI, G. R., and ANTOLOVICH, S. D. *Low Cycle Fatigue of a High Strength Metastable Austenitic Steel.* Met. Trans., v. 5, no. 1, 1974, p. 217-229.
6. LUTHER, R. G., and WILLIAMS, T. R. G. *The Influence of Phase Transformation in Stainless Steel During Static and Fatigue Loading.* Metal Science, v. 11, no. 6, June 1977, p. 219-224.
7. ZACKAY, V. F., PARKER, E. R., FAHR, D., and BUSCH, R. *The Enhancement of Ductility in High-Strength Steels.* Trans. ASM, v. 60, no. 1, 1967, p. 252-259.

80% in the temperature range 400 to 850 F (480 to 730 K). Melt compositions and further processing details are given in References 8 and 9.

Preliminary room-temperature tension tests revealed that the as-extruded material was too stable with respect to martensitic transformation during testing, resulting in lower than expected values of uniform elongation. A tempering treatment designed to alter the austenite matrix composition through carbide precipitation was found to restore the correct austenite stability for optimum room-temperature tensile properties. A one-hour temper at 1100 F (870 K) produced a markedly increased uniform elongation along with a higher ultimate tensile strength and a slightly improved reduction of area. The overall tensile properties of the extruded and tempered material were superior to those of warm-rolled material; the tensile results are discussed in detail in Reference 9 and summarized in Table 1. In the current study both the as-extruded and the tempered materials were examined to compare materials of differing stability, thus allowing an assessment of the influence of the deformation-induced transformation.

Load-controlled uniaxial high-cycle fatigue tests were conducted at room temperature on an SF-10U Satec fatigue machine at a frequency of 30 Hz and an R ($\sigma_{min}/\sigma_{max}$) ratio of 0.1. Cylindrical smooth fatigue specimens having a minimum diameter of 0.200 in. (0.508 cm) at the center of a slightly tapered gage section were used. The specimen threads were grit blasted to eliminate thread fatigue failures during testing.

RESULTS AND DISCUSSION

Figure 1 shows the S-N curves (maximum stress versus number of cycles to failure) for the materials extruded to reductions of 40, 60, and 80% and the tempered materials. Both vacuum and air-melted materials were tested in the as-extruded condition, while only vacuum-melted material was tested in the tempered

Table 1. TENSILE PROPERTIES OF EXTRUDED TRIP STEEL (Reference 9)

Reduction of Area, %	Condition	0.2% Y.S. ksi	0.2% Y.S. MN/m^2	U.T.S. ksi	U.T.S. MN/m^2	Elon.* %
40	As-Extruded	145	1,000	159	1,100	13
	Tempered†	136	938	199	1,370	41
60	As-Extruded	211	1,450	212	1,460	37
	Tempered†	207	1,430	228	1,570	40
80	As-Extruded	244	1,680	261	1,800	12
	Tempered†	258	1,780	271	1,850	44

*Elongation obtained from 1-inch (2.54 cm) gage marks on specimen (length/diameter = 5)
†Temper Treatment: 1 hour at 1100 F (870 K)

8. GAGNE, R. A., AZRIN, M., and DOUGLAS, J. R. *Warm Extrusion of TRIP Steels.* Army Materials and Mechanics Research Center, AMMRC TR 76-2, January 1976 (AD A022710).
9. AZRIN, M., OLSON, G. B., and GAGNE, R. A. *Austenite Stability and Tensile Properties of Warm-Extruded TRIP Steels* in Proceedings Fourth North American Metalworking Research Conference, T. Altan, ed., Battelle Columbus Laboratories, Ohio, 1976, p. 25-28.

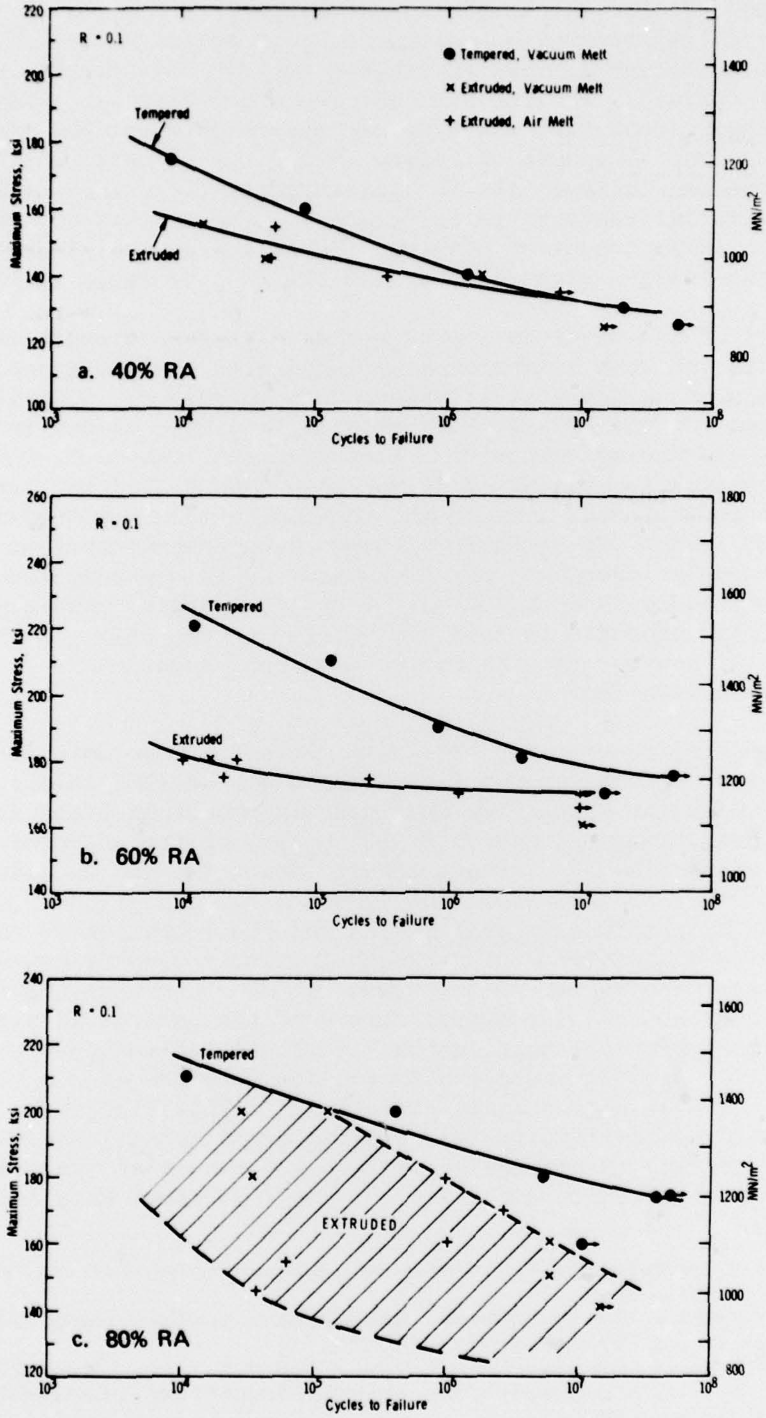

Figure 1. S-N curves of extruded TRIP steel. R=0.1, arrows indicate runout.

condition. The data for the as-extruded materials in Figures 1a and 1b indicate no significant difference between vacuum and air-melted materials. However, there is clearly a significant difference between the S-N curves of the as-extruded and the tempered materials. In line with the increased ultimate tensile strength, the less stable tempered material has significantly higher fatigue strength, particularly at low cycles. The data of Figure 1b for the 60% extruded material indicates that tempering improves the fatigue strength even at 10^7 cycles. For the 80% extruded material represented in Figure 1c, the results for the as-extruded material show a large amount of scatter. Tempering greatly reduced the scatter and improved the fatigue strength over the entire life range examined.

While most of the observed improvement in fatigue strength after tempering is likely due to the work hardening associated with the increased amount of deformation-induced martensitic transformation (higher U.T.S.), reduction in scatter observed for the 80% extruded material may also be due in part to relief of residual stress during tempering. Extrusion can lead to an undesirable residual stress distribution.[10] This may also account for an observed slight improvement in reduction of area in the tension tests after tempering.[9] Some of the improvement in fatigue strength at high cycles, where fatigue crack initiation becomes increasingly important, may be related to the heterogeneous nature of the deformation-induced transformation on a very local scale. The same concentrated dislocation arrays expected to initiate fatigue cracks (e.g., persistent slip bands) are likely sources for the dislocation configurations believed responsible for martensitic nucleation.[11]

Having found evidence for a beneficial effect of the deformation-induced martensitic transformation on the fatigue strength of TRIP steels, it is of interest to compare the properties obtained with those of other steels. Figure 2 shows the measured fatigue strength at 10^7 cycles of the extruded and tempered TRIP steel as a function of ultimate tensile strength, and includes available data for other steels tested under the same R = 0.1 conditions. Data are presented for both conventionally processed[12] and ESR (electroslag remelt) processed[13] 4340 steels tempered to different strength levels, including conventionally processed 300M (silicon-modified 4340),[12] and for HP 9-4 nickel-cobalt alloy steels of two carbon contents.[14] The overall trend of the data is in agreement with the observed behavior under the more common R = -1.0 condition that the fatigue strength increases proportionately with tensile strength at low strength levels, but then levels off at high tensile strengths.[15] This flattening has been attributed to increased susceptibility to corrosive environmental interaction[16] as well as greater sensitivity to surface condition as a result of the greater notch sensitivity of high-strength materials.[15] The TRIP steel data indicate that the

10. MIURA, S., SAEKI, Y., and MATUSHITA, T. *Residual Stresses in Hydrostatically Extruded Carbon Steel Rods.* Metals and Materials, v. 7, no. 7, 1973, p. 441-447.
11. OLSON, G. B., and COHEN, M. *A General Mechanism of Martensitic Nucleation: Part I. General Concepts and the FCC→HCP Transformation.* Met. Trans. A., v. 7A, no. 12, 1976, p. 1897-1904.
12. *Metallic Materials and Elements for Aerospace Vehicle Structures,* MIL-HDBK-5B, Chapter 2, August 31, 1973.
13. HICKEY, C. F., Jr. *Mechanical Property Survey of Electroslag Remelt Processed Steels.* Army Materials and Mechanics Research Center, AMMRC MS 74-4, March 1974.
14. *The 9Ni-4Co Steels,* DMIC Report 220, October 1, 1966 (AD 801977).
15. DIETER, G. E. *Mechanical Metallurgy.* McGraw-Hill Book Company, New York, 1961.
16. LEE, H. H., and UHLIG, H. H. *Corrosion Fatigue of Type 4140 High Strength Steel.* Met. Trans., v. 3, no. 9, 1972, p. 2949-2957.

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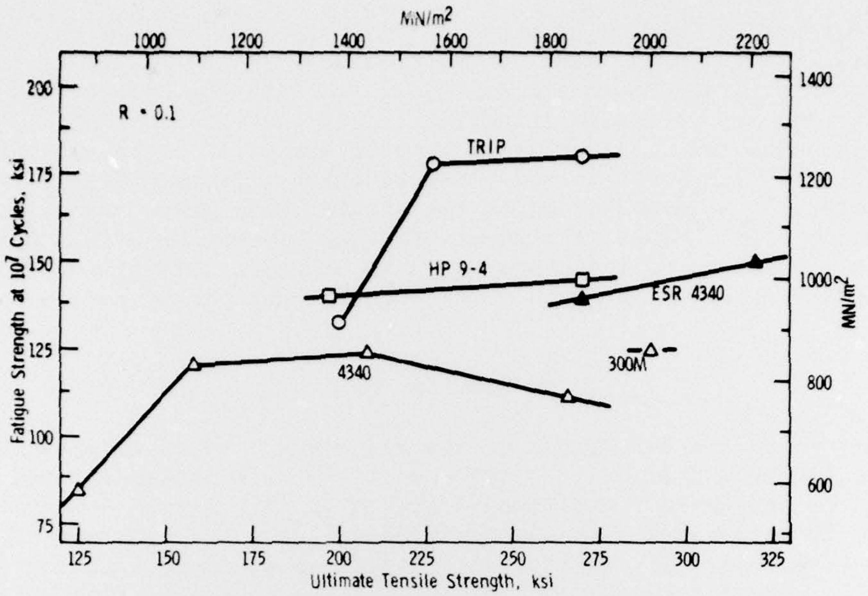

Figure 2. Fatigue strength at 10^7 cycles (R=0.1) versus ultimate tensile strength for high-strength steels. Tempered TRIP steel results are compared with available data for conventionally processed 4340 and 300M steels (Ref. 12), ESR processed 4340 (Ref. 13), and HP 9-4 steels (Ref. 14).

flattening is delayed to higher strengths, allowing an unusually high fatigue strength of 180 ksi (1240 MPa) to be obtained. While TRIP steels show moderate resistance to stress corrosion cracking (K_{ISCC} = 34 ksi$\sqrt{\text{in.}}$ or 37 MPa$\sqrt{\text{m}}$ for 70% warm-rolled material),* it is difficult to predict their resistance to corrosion fatigue. The high relative fatigue strength is most likely associated with low notch sensitivity as a result of the toughening effect of transformation plasticity.[17,18] Notched tension tests on the same material studied in this investigation revealed notch strength ratios (notch tensile strength/ultimate tensile strength) greater than unity even at the highest strength level.†

It is interesting to note that the 40% extruded material, in addition to showing the least attractive relative fatigue properties as represented by Figure 2, showed the smallest increase of fatigue strength after tempering despite a greater increase in ultimate tensile strength. Some fatigue tests of the 60% and 80% extruded materials in both the as-extruded and tempered conditions were conducted on a 10,000-lb (4500-kg) MTS closed test system, allowing examination of undamaged fracture surfaces in the scanning electron microscope after testing. Although there was some evidence of crack initiation at alumina inclusions, the

*W. F. Czyrklis, AMMRC, personal communication, 1977.

†G. B. Olson, R. A. Gagne, M. Azrin, AMMRC, unpublished data, 1976.

17. GERBERICH, W. W., HEMMINGS, P. L., ZACKAY, V. F., and PARKER, E. R. *Interactions Between Crack Growth and Strain-Induced Transformation* in Fracture 1969: Proceedings of the Second International Conference on Fracture, Brighton, April 1969, P. L. Pratt, ed., London, Chapman and Hall Ltd., London, 1969, p. 288-305.

18. ANTOLOVICH, S. D., and SINGH, B. *On the Toughness Increment Associated with the Austenite to Martensite Phase Transformation in TRIP Steels.* Met. Trans., v. 2, no. 5, 1971, p. 2135-2141.

surfaces indicated a large component of intergranular fracture which was most pronounced in the tempered material, particularly in the region of final fracture. The intergranular cracking is likely associated with the strong tendency for grain boundary carbide precipitation in austenites of such high chromium and carbon content. The monotonic tension tests as well showed an intergranular fracture mode together with many surface microcracks which were most severe in the 40% extruded material, apparently due to the greater mean grain boundary length normal to the tensile axis. Hence, the poorer fatigue properties of the 40% extruded material may be due to an influence of grain shape on intergranular cracking. This warrants caution in the use of TRIP steels warm-worked to low reductions.

CONCLUSIONS

Comparison of the S-N curves of the as-extruded material with those of the less stable tempered material indicates that the deformation-induced martensitic transformation increases the fatigue strength of TRIP steels under stress-control conditions, in accordance with observations on lower strength metastable austenites. The proportionality of fatigue strength to ultimate tensile strength is maintained to higher strength levels allowing the achievement of a fatigue strength at 10^7 cycles (for $R = 0.1$) of 180 ksi (1240 MPa).

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